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13. ABSTRACT (Maximum 200 words) This report summarizes the ARO- and NSF-sponsored "Bilateral US/Russian Workshop on Self-Propagating High-Temperature Synthesis" that was held on November 6-7, 1993, in Honolulu, Hawaii. The workshop focused on the fundamental as well as the applied aspects of the self-propagating high-temperature synthesis (SHS) process. The goal of the discussion of the fundamental topics was to identify—and suggest approaches to remedy--the generally acknowledged gaps that exist in our detailed, quantitative understanding of the essential chemistry and physics of the SHS process. The goal of the discussion of the applied topics was to focus on the rather more practical aspects of the SHS process, in order to help prioritize our fundamental studies in such a way that our enhanced understanding leads to improved SHS-based advanced materials fabrication methods. [The two topic areas are of course interrelated: Fundamental studies can enhance commercialization potential, and technological, market-driven needs can suggest important fundamental, science-driven studies.] The workshop also allowed many of the world's key, presently active SHS researchers to (i) discuss the state-of-the-art, and remaining work, of SHS research, and (ii) initiate meaningful collaborative research projects between US and Russian scientists.

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Report on the ARO/NSF Bilateral US/Russia Workshop on Self-Propagating High-Temperature Synthesis

November 6-7, 1993

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March, 1994

EXECUTIVE SUMMARY

This report summarizes the ARO- and NSF-sponsored "Bilateral US/Russia Workshop on Self-Propagating High-Temperature Synthesis" that was held November 6-7, 1993, in Honolulu, Hawaii. The workshop focused on the fundamental as well as the applied aspects of the self-propagating high-temperature synthesis (SHS) process. The goal of the discussion of the fundamental topics was to identify--and suggest approaches to remedy--the generally acknowledged gaps that exist in our detailed, quantitative understanding of the essential chemistry and physics of the SHS process. The goal of the discussion of the applied topics was to focus on the rather more practical aspects of the SHS process, in order to help prioritize our fundamental studies in such a way that our enhanced understanding leads to improved SHS-based advanced materials fabrication methods. [The two topic areas are of course interrelated: fundamental studies can enhance commercialization potential, and technological, market-driven needs can suggest important fundamental, science-driven studies.] The workshop also allowed many of the world's key, presently active SHS researchers to (i) discuss the state-of-the-art, and remaining work, of SHS research, and (ii) initiate meaningful collaborative research projects between US and Russian scientists.

After suggesting and discussing the crucial areas of SHS research that require significant attention, the workshop participants agreed to the following recommendations in the following areas:

- Detailed experimental studies of the micromechanistic details (i.e., on the particle scale and below) of the process are required.
- Detailed experimental studies on the key factors that influence the intermediate and final microstructure of the SHS-fabricated material are required.
- Comprehensive theoretical models are needed to help quantify and to enhance our understanding of the SHS process.
- Applications of the SHS process to the fabrication of advanced materials must be considered, in order to focus on the key problems to which our fundamental studies might be directed.

In addition, the outcome of the bilateral US/Russia workshop was that we were able to accomplish the following:

- The state-of-the-art needs of SHS research were discussed by the key researchers from both countries.
- Potentially supportable, mutually beneficial, collaborative SHS research projects were identified.
- Concrete plans to secure financial support for the collaborative projects were made.

TABLE OF CONTENTS

INTRODUCTION

The fabrication of high-performance materials that are highly resistant to environmental degradation (e.g., exposure to extreme thermal, chemical, mechanical and thermomechanical loads) is an important objective of various commercial and national security concerns because of the significant impact these materials will have in improving the performance of, e.g., high-temperature engine components, armor, and thermal barriers in propulsion systems. A prerequisite to the routine manufacture of optimal high-performance materials is, of course, a fundamental understanding of the key factors that influence the fabrication procedure. Only then can high-quality, high-reliability and low-cost advanced materials be expected to become available.

Several methods are available for fabricating oxide and non-oxide ceramic--as well as intermetallic--compounds for these purposes, but often produce materials with limited upper-use temperatures and limited thermal shock resistance. One of the more promising approaches is the "SHS" method.

Self-propagating high-temperature synthesis (SHS) is, in the most simple sense, the exploitation of an exothermic and usually very rapid chemical reaction to form a useful material. A key feature of the process is that the heat required to drive the chemical reaction is supplied from the reaction itself, and not from an external and therefore expensive source. Materials that have been successfully synthesized include carbides, borides, nitrides, oxides, intermetallics and rather complex composites. Important applications include electronic materials, and wear-, corrosion- and heat-resistant materials.

Successful fabrication by SHS requires a detailed understanding of the process. Unfortunately, a complete, quantitative connection between (i) the type, amount and distribution of constituent phases and pores in the as-synthesized product material and (ii) the size, purity and size distribution of starting materials has not been established. A fundamental understanding of the SHS process will only be achieved when combined experimental and theoretical investigations of the factors influencing, and the sub-processes that occur during, the SHS process are made. The essential chemistry and physics of the small- and large-scale events known or suggested to occur during the SHS process must be explicitly accounted for. Studies are therefore needed that account for the important sub-processes at the particle/pore (10^{-6} m) level in its description of the process at the sample (10^{-2} m) level.

This workshop represented an important attempt to develop a thorough, fundamental understanding of SHS. This understanding will require a macrokinetic (that is, mechanistic) framework that accounts for the distinguishing features of the process: examples include local melting, liquid redistribution, vapor phase formation, intrinsic chemical reaction kinetics, heat transfer, diffusion, supersaturation, and nucleation and crystallization of the product phase. The framework established in this way will lead to a much greater control of the process, and in turn the microstructure and properties of the material--particularly functional ceramic and ceramic-containing material--produced by the SHS process. Success in such an effort is likely only if a pooling of experience, knowledge and resources is made possible through a well-orchestrated Russia/US collaborative effort (the mechanism for which was established at this bilateral workshop).

The workshop was divided into two portions: fundamental and applied SHS research. This was done since it was recognized that (i) the two areas are, in practice, rather difficult to

separate (except along decidedly artificial and arbitrary lines), and (ii) the two areas are synergistic (to the benefit of both areas). First, the fundamental aspects of SHS were discussed. Both theoretical and experimental studies were considered, in order to develop a detailed, fundamental understanding of the process. Second, the applied aspects of SHS were considered, with particular reference to ceramic and intermetallic compounds. The practical needs of advanced materials fabrication efforts discussed there helped us to compile a useful list of research topics that might be through of as "directed basic" studies of SHS. Taken together, this discussion of fundamental and applied research allowed us to identify the most pressing needs of the SHS efforts in both countries.

FUNDAMENTAL ASPECTS OF SHS

A basic understanding and quantitative interpretation of the SHS process is required, in order for SHS to join the ranks of generally accepted materials fabrication processes. A combined theoretical and experimental approach is required to develop such an understanding. One day of the workshop was thus devoted to the fundamental aspects of the SHS process, such that two 1/2-day sessions were devoted to theoretical studies and experimental studies, respectively.

Fundamental Theoretical Studies

To date, considerable theoretical progress has been made in the study of SHS processes. Thermodynamic studies have given equilibrium phase distributions for a non-equilibrium process. Kinetic studies have begun to focus on one or more of the important sub-processes that are known to occur. Theoretical modelling studies have been performed--although usually for one-dimensional propagation and always with an oversimplified (but computationally expedient) description of the sample's microstructure. The SHS process is in fact a complex process that takes place in a complex system: the sample is typically a multiphase, multicomponent, reacting system in which reactants are converted to product(s) in an exceedingly short period of time. As a result, the participants recommended the following studies, in order to extend the present state of knowledge concerning the theoretical aspects of the SHS process:

- Extend the theoretical calculations using 2- and 3-dimensional models.
- Incorporate a greater degree of microstructural detail into the models.

Higher-dimensional models are essential to the development of an improved understanding of the SHS process. In practice, most SHS samples are of finite dimension (i.e., they possess edges and corners). These gross structural features often result in the formation of inhomogeneous products and/or unstable combustion wave propagation. The source of these difficulties is likely the spatial non-uniformities in heat transfer, diffusion, fluid flow and deformation phenomena that arise in the sample during the process; simply put, the sample "burns" differently along the edges than it does in the center. Two- or three-dimensional models deal properly with these edge effects, and thus promise to lend great insight into key features of the SHS process. The concomitant increase in the need for additional computing resources would of course be justified in light of the increased understanding of the process that would result.

Microstructural detail must be incorporated into all future theoretical modelling efforts. Since the usefulness of theoretical results depends directly on the number and the reasonableness

of the simplifying assumptions that are made in the construction of a model, it is quite clear to existing SHS practitioners that past theoretical efforts have been severely hampered by (often unnecessary) oversimplifications. This is nowhere more true than in the specification of microstructural features of reactants, intermediates and product, but also in the details of the local, particle-scale chemical interactions that drive the process, and the nucleation and growth of product phases. In particular, the local physical and chemical events--both in the combustion front itself and in the zone immediately behind the combustion front--are rarely described in sufficient and quantitative detail in models of the overall SHS process. It is only when these microstructural details are expressed clearly, precisely and with sufficiently realistic and quantitative detail that a complete theoretical model will be developed. [Of course, the macroscopic details that are common in the earlier models, such as mass transfer and heat transfer, would be included.]

A list of specific topics, concerning the fundamental theoretical aspects of the SHS process, that was generated during the workshop is given in Appendix 1.

Fundamental Experimental Studies

Fundamental experimental studies of the SHS process comprise perhaps the greater fraction of effort that has in the past been devoted to developing a fundamental understanding of the SHS process. Many good, empirical studies have been conducted, especially those that focus on certain gross, easily measured features of the sample and its behavior during the SHS process. They have focused on the effect of such things as particle size, green density, gas pressure, etc., on the temperature, wave velocity, final distribution of product phases, and so on. From this, some inferences could be made about the basic mechanisms that lead to self-propagating behavior. Unfortunately, less attention has been given to more direct--particularly *in situ*--elucidation of the fundamental mechanisms that drive the SHS process. As a result, the participants recommended that the following studies be conducted, in order to extend the present state of knowledge concerning the experimental aspects of the SHS process:

- Conduct *in situ* experiments that focus on the real-time details of intermediate and product phase formation.
- Conduct definitive studies of the factors that influence the structure of the condensed phases and pores in the sample.
- Determine the influence of external fields on the behavior of the combustion wave and the products that result.
- Develop a quantitative understanding of the effects of an applied mechanical load on the SHS process (particularly with respect to enhanced densification).

The formation of intermediate and product phases is presently not well understood. The high temperatures that are characteristic of the SHS process, along with the speed with which the process occurs, have made it quite difficult to detect the disappearance of reactant materials, the appearance and disappearance of intermediates phases, and the appearance of product phases in a clear and direct manner. Approaches that were suggested at the workshop include real-time x-ray diffraction (using a high-energy syncrotron source or a high-intensity x-ray tube) and video-recording (using an optical microscope) to observe and record the behavior of an SHS sample during the process. Detailed, *in situ* observation should provide great insight into the dynamics of phase formation during the SHS process.

The factors that influence the structure of the condensed phases and pores in the sample must be known with greater certainty than at present. More specifically, it is important to understand in greater detail the (separate and combined) effects of fluid flow, heat transfer (radiative, conductive and convective), and mass transfer on the evolution of the sample's microstructure during the SHS process. This is particularly true in the case of microengineered composite materials and in objects where strict control of porosity is essential.

The influence of external fields on the progress and outcome of an SHS progress is in many cases profound. Complete knowledge of the mechanism by which this occurs is not, however, available. For example, conducting the SHS process in a centrifugal field may promote full densification of a sample (that would otherwise be highly porous if the process were conducted in the absence of a centrifugal field). Alternatively, microgravity conditions have been suggested as an interesting modification of this approach, although it is not yet clear what the expected benefits might be. In addition, the SHS process may also be modified by application of electromagnetic energy, in the form of a radio frequency field or microwave energy, in order to heat the sample to the point of ignition or to sustain an otherwise weakly self-propagating reaction. It is likely that each of these modifications alters the various momentum, energy, mass and electromagnetic transport phenomena that occur during the SHS process. A complete understanding of the process requires that the influence of these modifications be accounted for explicitly and understood thoroughly.

Further, a mechanical load may be applied to the reacting sample, in order to produce a dense material. The applied load may influence the SHS process in at least two ways. First, at a relatively low pressure and low strain-rate, the timely application of a mechanical load may exploit the brief appearance of a liquid phase and/or high-temperature ductility that exist in (or near) the zone of the combustion front to densify the sample in that zone. [The zone is much more easily compressed when some or all of the zone is liquefied at the elevated process temperatures.] Second, at a relatively high pressure and high strain-rate, the load may actually initiate the self-propagating reaction. [A solid-to-liquid phase transition may occur under high-strain-rate loading conditions, as a result of the temperature increase that is associated with shock compression under essentially adiabatic conditions, which in turn promotes greater contact between reactant phases--thus initiating the SHS process.] Again, it is likely that each of these modifications alters the various momentum, energy and mass transport phenomena that occur during the SHS process. These influences must be studied in order to develop an understanding--and thus an enhanced degree of control--of the SHS process. In particular, constitutive relationships must be developed to link the sample's response to a given loading condition.

A list of specific topics, concerning the fundamental experimental aspects of the SHS process, that was generated during the workshop is given in Appendix 2.

APPLIED ASPECTS OF SHS

The development of advanced materials currently receives a great deal of attention because of the significant improvements in performance that they promise--particularly with respect to the fabrication of high-performance materials that are highly resistant to environmental degradation (e.g., exposure to extreme thermal, chemical, mechanical and thermomechanical loads). The SHS process is well suited to produce many of the materials that are required in the ongoing materials revolution. Not all suggested applications have yet been realized, however, since not all aspects

of their fabrication have been well understood (much less controlled). As a result, analysis of the needs of the applications for these advanced materials is of central importance to the SHS materials scientist. In fact, it is usually impossible to separate the more basic SHS research effort from its applications-driven counterpart--since the two efforts are distinctly synergistic and often lead to a beneficial cross-fertilization. The second day of the workshop was therefore devoted to applications, in order that some so-called "real" problems might be identified for future fundamental study. Two sessions were held: one that focused on ceramic materials and ceramic-matrix composites, and a second that dealt with intermetallic materials and intermetallic-matrix composites--two classes of materials that are of significant interest in both the near- and long-term.

Ceramics and Ceramic-Matrix Composites

The SHS process has been used to produce a wide variety of ceramic materials. Materials that have been successfully synthesized include carbides, borides, nitrides, oxides, and even phosphides and sulfides (i.e., M_XC, M_XB, M_XN, M_XO, M_XP, and M_XS, where M is typically a transition metal), in the form of powders, monoliths, coatings and composites. The work to date is largely empirical, however, which may limit the commercialization potential of many manufacturing schemes that might be implemented. As a result, the workshop participants suggested two focus areas in which more fundamental (as well as related applied) research is sorely needed:

- Extend the SHS process to produce ceramic materials with submicron- and nanometer-scale features (that is, $10^{-6} \rightarrow 10^{-9}$-m microstructural features).
- Establish a quantitative protocol for producing controlled-porosity ceramic materials.

The fabrication of ceramic materials with nanoscale features by the SHS process can of course begin by applying existing, empirically derived knowledge to the task. It is likely, however, that additional information will be required, since the combined presence of a liquid phase and the characteristically high reaction temperatures will make it difficult to retain an ultrafine microstructure in the product material. [Both are likely to lead to coarsening of any nanoscale features of starting materials and intermediate phases that might be present for a time before the process has been completed.] This will obviously require that the SHS process be controlled to a much greater degree than is possible at present. Much of the "new knowledge" that is required here will undoubtedly come from the combined fundamental experimental and theoretical studies that were described, above.

The fabrication of ceramics with controlled porosity may, on the other hand, be somewhat more straightforward, since the typical product of an SHS process is a porous object (of the target ceramic material) in which the ceramic grains are partially sintered. In the absence of an applied mechanical load, the outcome of an SHS process is usually a sample that contains (with respect to a conventional materials development effort) an unacceptably high degree of porosity. If one relaxes this requirement of high density, a number of useful applications manifest themselves: porous materials become the desired product, rather than a "failure." For many applications to be realized, however, specific control of the SHS process will be needed, in order to prepare shaped materials that have the porosity, a pore size distribution, and pores with sufficiently high degree of connectivity that are required to meet the performance requirements of the specific application.

Again, this will obviously require that the SHS process be controlled to a much greater degree than is possible at present--thus suggesting a variety of fundamental studies that must be conducted.

A list of specific topics, concerning the applications of the SHS process to the fabrication of ceramics and ceramic-matrix composites, that was generated during the workshop is given in Appendix 3.

Intermetallics and Intermetallic-Matrix Composites

As with ceramic-based materials, the SHS process has been used to prepare a number of monolithic and composite intermetallic materials. Particularly significant are the aluminides, silicides, and nickelides (e.g., NiAl, Ni_3Al, TiAl, Ti_3Al, $MoSi_2$, Ti_5Si_3, and NiTi), which hold promise for a number of applications which require a high-temperature material that has low density, and good high-temperature stability, and wear- and oxidation-resistance. It is known from the literature, however, that modifications of certain intermetallic materials are required to enhance the room-temperature ductility (i.e., brittleness) and elevated-temperature creep resistance. As with the non-SHS approaches to overcoming these difficulties, the workshop participants suggested that these two focus areas which are of the utmost importance require more fundamental (as well as related applied) research:

- Develop a method to produce dense, reinforced intermetallic-matrix composites.
- Demonstrate the effectiveness of using the SHS process to synthesize alloyed intermetallic compounds.

The reinforcement of intermetallic materials with inclusions (by non-SHS-based procedures) has in some cases resulted in dramatic improvements in the strength and creep resistance in the host intermetallic material. In this regard, reinforcements in the form of particles, whiskers, platelets, chopped fibers, and continuous fibers have been added--with the use of continuous fibers having the most significant positive effect. It is thus necessary for studies to be conducted that ensure (i) that the intermetallic matrix phase is synthesized by the SHS process, and (ii) that the intermetallic matrix phase is caused to infiltrate a continuous-fiber preform (and achieve full density in the process). Care must be taken that no deleterious interphase reactions or interactions occur. The somewhat more complex nature of the sample's microstructure--before, during and after the process--requires that new, fundamental knowledge be acquired. Only in this way can the commercialization potential of the SHS process for producing intermetallic-matrix composites be realized.

Addition (using conventional fabrication techniques) of alloying elements to intermetallic compounds has also led to significant improvements in certain key properties. For example, the addition of 0.1 wt% boron to Ni_3Al significantly increases the room-temperature ductility of Ni_3Al, and also enhances its oxidation resistance. Numerous other examples of such improvements in key material properties have been reported in the literature. This topic is thus one that merits significant attention from SHS research scientists. In particular, it is not always the case that "impurities" are incorporated into the compound that is synthesized by the SHS process: volatilization may occur at elevated SHS temperatures (and the alloying element would thus lost from the sample), or incomplete reaction may occur on the SHS time-scale (and the alloying element would thus remain as a discrete second phase). This is also a somewhat more complicated sort of system, and will require consideration of rather fundamental details, in order

for the SHS process can displace competing technologies for the fabrication of alloyed intermetallic compounds.

A list of specific topics, concerning the applications of the SHS process to the fabrication of intermetallics and intermetallic-matrix composites, that was generated during the workshop is given in Appendix 4.

CONCLUDING REMARKS

The bilateral US/Russia workshop on SHS was considered a success by the workshop participants--according to several measures. First, key Russian and US researchers, who have had limited personal interaction in the past, were able to meet those with similar interests. Numerous working relationships were initiated between those with overlapping interests and complementary skills and expertise. The workshop was an efficient means by which longer-term collaborative research efforts could begin. Second, many topics for collaborative research projects were suggested and shaped by the scientists who would also be conducting the research. Since it was recognized that some of the topics were more likely to receive support than others, an effort was made to prioritize the list of suggested topics according to this criterion (tempered of course by the wants and needs of the individual scientists themselves). Third, some discussion was devoted to matching the scientists and their topic(s) to the appropriate governmental or private funding agency that might support the topic(s). These three focal points were each properly addressed during the workshop--thus laying a solid foundation on which a significant, longer-term research collaboration between the US and Russian SHS communities can be built.

With this done, the next obvious step is for individual scientists in both countries to prepare joint research grant proposals to submit to the appropriate agencies. Some concrete steps were taken while the scientists were together in Honolulu. Others have been taken (principally by electronic mail) following the conclusion of the workshop. At this point, it is up to the individual scientists who were "matched" at the workshop to secure financial support for their proposed, small (i.e., two- or three-investigator) projects in the normal, peer-review process.

WORKSHOP SCHEDULE

Saturday, November 6, 1993

Session I: Workshop Introduction and Theoretical Aspects of SHS

9:30 A.M.	Welcome and Introductions	Stangle, Spriggs and Merzhanov
9:45 A.M.	Workshop Outline	Stangle
10:00 A.M.	How U.S./Russia Collaborative Research Is Supported	Stangle for Dr. Milton Linevski
10:15 A.M.	Presentations	Stangle, Zhirkov and Panelists
11:30 A.M.	Session I Discussion	Stangle, Zhirkov and Participants
12:30 P.M.	Develop Consensus of Theoretical Aspects	Stangle, Zhirkov and Participants
1:30 P.M.	Lunch	Participants

Session II: Experimental Aspects of SHS

2:30 P.M.	Presentations	Munir, Rogachev and Panelists
3:50 P.M.	Session II Discussion	Munir, Rogachev and Participants
5:00 P.M.	Develop Consensus of Experimental Aspects	Munir, Rogachev and Participants

Sunday, November 7, 1993

Session III: Advanced Materials - Including Applications (Ceramics and CMCs)

8:30 A.M.	Presentations	Spriggs, Borovinskaya and Panelists
10:15 A.M.	Session III Discussion	Spriggs, Borovinskaya and Participants
11:00 A.M.	Develop Consensus of Advanced Materials	Spriggs, Borovinskaya and Participants
12:00 P.M.	Lunch	Participants

Session IV: Advanced Materials including Applications (Intermetallics and IMCs)

2:00 P.M.	Presentations	Moore, Yukhvid and Panelists
2:45 P.M.	Session IV Discussion	Moore, Yukhvid and Participants

Session V: Consensus of Workshop

4:00 P.M.	Summary remarks	Stangle, Spriggs and Merzhanov
4:30 P.M.	Preliminary report preparation	Session Chairs

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Appendix 1: Specific Topics - Fundamental Aspects (Theoretical)

1. Chemical mechanism
2. SHS in reactive gas
3. Particle-scale chemistry
4. Powder characteristics
5. Microstructure (including polymorphic transformation)
6. SHS-densification/shape-forming/melting
7. Melting/spreading
8. Deformation
9. Heat Loss
10. Multilayers
11. Irregular combusion waves
12. External fields
13. Macrostructure
14. Electro/thermal explosion
15. Residual stresses
16. Combustion - engineering materials

Appendix 2: Specific Topics - Fundamental Aspects (Experimental)

1. Time-resolved methods for studying SHS "in situ"
2. Microstructural control - micro & macrostructure control - mechanism: how does product form?
3. Particle-foil & multi-layer model experimental combustion of "layered systems"
4. Methods for micro-structure and crystal structure control
5. Control of macro-and microparameters, & their connection
6. Porosity/densification consideration
7. Role of electromagnetic field
8. Electrothermal explosion
9. Role of reactive & non-reactive gases in SHS
10. Gravitational effects
11. Role of impurities
12. SHS - diagrams
13. Thin films/coatings
14. Single crystals
15. Gas-phase SHS in rocket engine
16. Foamed ceramics
17. Electrothermography
18. Forging of SHS products
19. Thermal shock-induced cracking
20. Microstructural evolution during and after densification

Appendix 3: Specific Topics - Applied Aspects (Ceramics, CMCs)

Oriented Basic Research

1. Complex oxides (ferro, HTSC, ferrites)
2. Chemistry (+ phases) vs. synthesis (w/organics)
3. SHS-derived ceramics - (Long List); $B_{6.5}$ C, AlN; granulometrics
4. Hi-speed densification (with near net shape, scale-up, etc.)
5. Centrifugal-SHS
6. Need for toughening - alloying, fibers, whiskers
7. One-step porcelain production
8. Parts - 1 step SHS; No grinding/comminution processes
9. Anisotropy of properties
10. Structural "statics" of SHS ceramics
11. Control of phase structure, aerodynamics, compaction/consolidation, mechanisms, separation of phases, (i.e., intermetallic + oxide, solid from liquid state)
12. Combustion mechanisms
13. Sintering and "After Sintering"
14. Si_3N_4 - ISMAN
15. $TiB_2 + ZrO_2$ (tet)
16. Nanoparticle synthesis - flash pyrolysis, etc.
17. Joining
18. Functionally Gradient Materials
19. Thin Films
20. Membranes
21. SHS-extrusion
22. Coatings by SHS
23. Shape-memory materials
24. Superconductors
25. Gas absorbers
26. Electrodes
27. Biomedical materials
28. Wrought products
29. Single crystals by SHS

Appendix 4: Specific Topics - Applied Aspects (Intermetallic, IMCs)

1. NiAl, FeAl, TiAl
2. Complex systems ceramics + metals (new matls), e.g., Ti-B, Ti-B-Fe, Ti-B-Ni
3. Silicides
4. Dispersed strengthening (composites)
5. Need for continuous fiber reinforcement - toughness + creep resistance.
6. Continuous fibers/wires
7. Simultaneous combustion + hot pressing: continuous ceramic fibers + NiAl
8. Layered intermetallic composities (laminated composites)
9. Diamond synthesis
10. Controlled porosity (by vacuum SHS rolling)
11. Intentionally porous system - implants for bone replacement
12. Relationships to phase diagrams of components
13. Intermetallics with improved heat-, wear-, corrosion-resistance
14. Structural composites
15. Catalysts